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13. ABSTRACT *(Maximum 200 words)*

This research is relevant to the Air Fore mission because pneumatic muscle actuation devices arc advantageous for certain types of robotics as well as for strength and/or mobility assistance for humans. For space robotics, PMs are advantageous because they require little electrical power (being pneumatically powered), are lightweight, and can be easily constructed from cheap, readily available materials. The fact that PMs require little electrical power means that heavy generators and/or batteness are not necessary. The fact that they are easily constructed from cheap, readily-available materials insures that an actuator failure need not hamper the mission.

Since PMs are similar in size and function to human muscles, PM systems can also be used to actuate exoskeleton frames worn by humans to enhance strength and provide mobility assistance for military operations in the field. A requirement exists for the building of strength augmentation devices to help military personnel perform certain tasks that require unusual strength for short periods of time. Such systems can be powered by pneumatic muscle actuators. According to the 1997 DoD Defense Technology Area Plan (STAR), "performance enhancement technologies support future joint warfighting needs in teleoperation and physical aiding."

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PNEUMATIC MUSCLE ACTUATOR CONTROL
(third year performance report)

GRANT # F49620-00-1-0300

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Objectives

1. Mathematical modeling of planar arm robotic configurations actuated as follows:

   (a) one PM in bicep position actuating elbow
   (b) one PM in tricep position actuating elbow
   (c) two PMs in bicep and tricep (agonist/antagonist) positions actuating elbow
   (d) four PMs, one agonist/antagonist pair actuating shoulder and one agonist/antagonist pair actuating elbow.

2. Investigation of:

   (a) adaptive control
   (b) fuzzy control
   (c) sliding mode control

   for joint angle and/or end effector tracking for all configurations in 1.

3. Proofs of stability for all algorithms in 2.

Status of Effort

Objectives 1(a), 1(b), 2(a), and 2(b) (partial) and corresponding stability proofs have been accomplished in previous years of grant. Remaining objectives have been accomplished in third year.

Accomplishments/ New Findings

1. Derivation of single-input sliding mode controller for planar arm actuated by two PMs [3], [6].

In this research, we derive a mathematical model for a planar arm assembly actuated by two PMs. This is done for the purpose of designing a sliding mode controller for elbow angle tracking control. In this arrangement, the elbow joint is actuated by PMs arranged in an opposing pair configuration, one acting in the place of a bicep and the other in place of the tricep. In this configuration, only the forearm is moved; the upper arm is stationary.

For modeling purposes, the Reynolds model of the PM is used [1]. This models each PM with a second-order nonlinear ODE consisting of friction and spring coefficients that are nonlinearly dependent on the input, which is the commanded PM internal pressure. By letting the bicep and tricep PM internal pressures be determined as

$$P_b = P_{b0} + \Delta p \tag{1a}$$

$$P_t = P_{t0} - \Delta p \tag{1b}$$

where P_{b0} and P_{t0} are constants chosen by the designer, the arm actuated by two PMs becomes a single-input system with input Δp. By correctly combining the dynamics of the mechanical system (i.e. the arm) with those of the PMs, an affine-in-the-input 2[nd]-order nonlinear model is obtained. This model is used to design a single-input sliding mode controller.

The entire system, consisting of the arm actuated by two PMs, together with the sliding mode controller, is simulated. For the simulations, it is assumed the parameters of the two PMs are poorly known (which they most certainly will be in practice). The sliding mode controller provides elbow angle tracking to within predicted error bounds. The effects of PM heating are also investigated via simulation (heating occurs due to friction as a result of increased PM use). A stability proof is obtained for the closed-loop system, in which the steady-state tracking error bounds are derived. Simulation results are in line with theoretically predicted error bounds.

The pressures P_{b0} and P_{t0} in (1) are nominal static internal PM pressures that can be determined by the designer. A relationship between P_{b0} and P_{t0} is derived in [6] to guarantee stable arm behavior in the absence of a control signal (i.e. if the control loop is broken).

2. Derivation of a two-input sliding mode controller for planar arm actuated by four PMs [7].

In this research, we derive a mathematical model for a planar arm assembly actuated by four PMs. This is done for the purpose of designing a two-input sliding mode controller for simultaneous shoulder and elbow angle control. In this arrangement, the shoulder joint is actuated by two PMs arranged on the torso in an opposing pair configuration, one causing the upper arm to be raised and the other causing the upper arm to be lowered. The elbow joint is actuated by two other PMs in opposing pair configuration, one in place of the bicep and the other in place of the tricep. Thus, in this configuration, both upper arm and forearm are moved, resulting in true 2-DOF movement.

For modeling purposes, the Reynolds model of the PM is used [1]. This models each PM with a second-order nonlinear ODE consisting of friction and spring coefficients that are nonlinearly dependent on the input, which is the commanded PM internal pressure. By letting the shoulder and elbow bicep and tricep PM internal pressures be determined as

$$P_{bs} = P_{bs0} + \Delta p_s \tag{2a}$$
$$P_{ts} = P_{ts0} - \Delta p_s \tag{2b}$$

$$P_{be} = P_{be0} + \Delta p_e \tag{3a}$$
$$P_{te} = P_{te0} - \Delta p_e \tag{3b}$$

where P_{bs0}, P_{ts0}, P_{be0}, and P_{te0} are constants chosen by the designer, the arm actuated by four PMs becomes a two-input system with inputs Δp_s and Δp_e. By correctly combining the dynamics of the mechanical system (i.e. the arm) with those of the four PMs, an affine-in-the-input 4th-order nonlinear model is obtained. This model is used to design a two-input sliding mode controller to control end effector (hand) position.

The entire system, consisting of the 2-DOF arm actuated by four PMs, together with the two-input sliding mode controller, is simulated. For the simulations, it is assumed the parameters of the four PMs are poorly known (which they most certainly will be in practice). The two-input sliding mode controller provides shoulder and elbow angle tracking to within predicted error bounds. The effects of PM heating are also investigated (heating occurs due to friction as a result of increased PM use). A stability proof is obtained for the closed-loop system, in which the steady-state tracking error bounds are derived. Simulation results are in line with theoretically predicted error bounds.

As above, the pressures P_{bs0} and P_{ts0} in (2) and P_{be0} and P_{te0} in (3) are nominal static internal PM pressures that can be determined by the designer. Relationships between both opposing-pair static internal pressures are derived to guarantee stable arm behavior in the absence of control signals (i.e. if the control loops are broken).

3. Neurofuzzy modeling of actual PM from data via EVISIT [5], [8].

The Evolutionary Variable Input Spread Inference Training algorithm (EVISIT) is a new algorithm for fuzzy classification and function approximation from data. EVISIT was developed as a result of this research. It is based on the VISIT algorithm, which is derived from the well-known Modified Learning From Examples (MLFE) algorithm. EVISIT seeks to construct a fuzzy classifier, or a function approximator for a nonlinear function, based on measured data from the process.

The identification process is briefly described as follows. First, the structure of the fuzzy system is identified using EVISIT. In this procedure, the inputs and number of membership functions on each universe of discourse are determined by the user. Then, the optimal VISIT parameters are determined via an evolutionary algorithm. Second, the resulting fuzzy system is expressed in neurofuzzy form, and the well-known error backpropagation algorithm is used to fine-tune all parameters of the fuzzy system, i.e. those of the input triangular membership functions. As is well known, if the inputs are chosen properly, EVISIT or any neurofuzzy system can be made to approximate a dynamical system.

We utilized input/output data taken from the PM test station at WPAFB in conjunction with EVISIT to derive a fuzzy model of the PM. The resulting fuzzy model has four inputs, 14 total input fuzzy sets, and 24 rules. This model was used in design and tuning of a fuzzy P+ID controller for the PM [4]. This controller performed better in lab experiments than a fuzzy model reference adaptive controller designed for this system over many trials [2] (an earlier result of this research). In addition, the fuzzy P+ID controller based on the EVISIT-tuned model required no tuning, but performed well on the first trial.

Relevance of this Research to AF Mission

This research is relevant to the Air Fore mission because pneumatic muscle actuation devices are advantageous for certain types of robotics as well as for strength and/or mobility assistance for humans. For space robotics, PMs are advantageous because they require little electrical power (being pneumatically powered), are lightweight, and can be easily constructed from cheap, readily-available materials. The fact that PMs require little electrical power means that heavy generators and/or batteries are not necessary. The fact that they are easily constructed from cheap, readily-available materials insures that an actuator failure need not hamper the mission.

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Relevance of this Research to Civilian Technology Challenges

This research also has applications to certain civilian technology challenges, such as assistance in movement for stroke victims and persons suffering from other physical disabilities such as Parkinson's disease and multiple sclerosis.

References

[1] D. B. Reynolds, D. W. Repperger, C. A. Philips and G. Bandry, "Dynamic characteristics of pneumatic muscle," *Annals of Biomedical Engineering*, March 2003.

[2] S. W. Chan, J. H. Lilly, D. W. Repperger, and J. E. Berlin, "Fuzzy PD+I Learning Control for a Pneumatic Muscle," *2003 IEEE International Conference on Fuzzy Systems (FUZZ-IEEE)*, St. Louis, May 2003.

[3] L. Yang and J. H. Lilly, "Sliding Mode Tracking for Pneumatic Muscle Actuators

in Bicep/Tricep Pair Configuration," *Proc. 2003 American Control Conference*, Denver, CO, June 2003.

[4] X. Chang and J. H. Lilly, "Fuzzy Control for Pneumatic Muscle Tracking via Evolutionary Tuning," *Autosoft – Intelligent Automation and Soft Computing*. To appear.

[5] X. Chang and J. H. Lilly, "Evolutionary Design of a Fuzzy Classifier from Data," *IEEE Trans. on Systems, Man, and Cybernetics*. Submitted.

[6] J. H. Lilly and Liang Yang, "Sliding Mode Tracking for Pneumatic Muscle Actuators in Opposing Pair Configuration," *IEEE Trans. on Control Systems Technology*. Submitted.

[7] J. H. Lilly and P. M. Quesada, "A Two-input Sliding Mode Controller for a Planar Arm Actuated by Four Pneumatic Muscles," *IEEE Trans. on Neural Systems and Rehabilitation Engineering*. Submitted.

[8] J. H. Lilly, X. Chang, and D. W. Repperger, "Pneumatic Muscle Modeling with EVISIT," *IEEE Trans. on Systems, Man, and Cybernetics*. To be submitted.

Personnel Supported

Dr. John H. Lilly
Dr. Xiaoguang Chang, Postdoctoral Associate
Mr. Liang Yang, Ph.D. student
Mr. Sui Wai Chan, Master's student (graduated Spring 2002)

Interactions

Conference papers:

S. W. Chan, J. H. Lilly, D. W. Repperger, and J. E. Berlin, "Fuzzy PD+I Learning Control for a Pneumatic Muscle," *2003 IEEE International Conference on Fuzzy Systems (FUZZ-IEEE)*, St. Louis, May 2003.

L. Yang and J. H. Lilly, "Sliding Mode Tracking for Pneumatic Muscle Actuators in Bicep/Tricep Pair Configuration," *Proc. .2003 American Control Conference*, Denver, CO, Junse 2003.

Numerous electronic communications with Dr. D. W. Repperger and J. E. Berlin at Human Sensory Feedback Laboratory at Wright Patterson AFB. The purpose of these was to test various controllers on the pneumatic muscle test station at WPAFB. Dr. Repperger and Mr. Berlin were kind enough to test our controllers and send us the data from many runs.

Dr. Lilly, Dr. Peter M. Quesada (Mechanical Engineering, U of Louisville), and five students visited Dr. Repperger at HSF WPAFB in Fall 2002 for the purpose of showing Dr. Quesada and the students the PMs in the HSF lab.

Publications from this grant (new for current year)

S. W. Chan, J. H. Lilly, D. W. Repperger, and J. E. Berlin, "Fuzzy PD+I Learning Control for a Pneumatic Muscle," *2003 IEEE International Conference on Fuzzy Systems (FUZZ-IEEE)*, St. Louis, May 2003.

L. Yang and J. H. Lilly, "Sliding Mode Tracking for Pneumatic Muscle Actuators in Bicep/Tricep Pair Configuration," *Proc. 2003 American Control Conference*, Denver, CO, June 2003.

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J. H. Lilly, X. Chang, and D. W. Repperger, "Pneumatic Muscle Modeling with EVISIT," *Autosoft – Intelligent Automation and Soft Computing*. To be submitted.